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RESEARCH MEMORANDUM

THE EFFECT OF INITIAL RATE OF SUBSONIC DIFFUSION ON THE STABLE SUBCRITICAL MASS-FLOW RANGE OF A CONICAL SHOCK DIFFUSER

By J. C. Nettles

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE EFFECT OF INITIAL RATE OF SUBSONIC DIFFUSION ON THE STABLE SUBCRITICAL MASS-FLOW RANGE OF A CONICAL SHOCK DIFFUSER

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SUMMARY

Results are presented of a systematic study made in the Lewis 8- by 6-foot supersonic wind tunnel to determine the effect that area distribution in the subsonic diffuser might have on the stability and overall performance of conical-type supersonic diffusers. Drag, pressure recovery, and mass flow are presented for five diffusers designed for maximum mass flow at a Mach number of 2.0. The diffusers had the same supersonic compression but different initial rates of subsonic diffusion.

Reducing the initial rate of subsonic diffusion was effective in improving the mass-flow range that could be achieved without pulsation. The diffuser with 3.5 hydraulic diameters of zero diffusion length at the entrance to the subsonic diffuser could be throttled for a range of 46 percent of maximum mass-flow ratio without oscillation. The incorporation of this zero diffusion in the subsonic diffuser had little if any effect on the critical pressure recovery at a Mach number of 2.0 and zero angle of attack. The stable range of the diffuser with 3.5 hydraulic diameters of stabilizing length had a tendency to improve with increasing angle of attack until a critical angle was reached, at which point the stable range suddenly decreased to a value just slightly better than the comparable diffuser without stabilizing length.

INTRODUCTION

Numerous experimenters have observed the tendency for diffusers with external compression to enter into a state of oscillation of both the sustained and random type when the air flowing through the diffuser is reduced below the maximum value. Several different concepts have been offered to explain this phenomenon.

The idea advanced in reference 1 is that the instability of supersonic inlet flow is due to disturbances propagating upstream in a decelerating flow and becoming trapped in a region of sonic flow, thus causing a redistribution or repositioning of the shock structure. This

author concludes that the installation of a length of constant-area passage at the entrance to the subsonic portion of the diffuser would allow these disturbances to be absorbed without causing a reflection downstream.

In reference 2 experimental data are presented which show that the insertion of a constant-area section in the throat of a convergent-divergent diffuser operating at a Mach number of 1.85 stabilized the dynamic system and permitted the peak pressure recovery to be obtained.

In reference 3 it is pointed out that a discontinuity in velocity may occur downstream of the intersection of the inlet shock waves, and the presence of this velocity discontinuity near the inner surface of a diffuser cowl acts like a flow separation in the subsonic diffuser which can cause oscillation of the entire flow system. This author reasons that a constant-area passage at the diffuser entrance would promote mixing and would therefore tend to reduce the effect of the velocity discontinuity. References 3 and 4 show that a constant-area section following the cowl of a conical-type supersonic diffuser was effective in increasing the stable subcritical mass-flow range.

The stability criterions of the dynamic diffuser system are studied in reference 5 in terms of the slope of the pressure-recovery mass-flow characteristics and the ratio of the oscillating-air column length to the storage volume of the diffuser likened to a Helmholtz resonator. An increase in the oscillating-air column length is shown to improve the stability for a given slope of the pressure-recovery curve. The installation of a constant-area passage at the entrance of the diffuser should also increase the effective air column length.

This report presents data on the effect of various rates of subsonic-diffuser area variation on the stable subcritical mass-flow range of conical supersonic diffusers designed for operation at a Mach number of 2.0. Pressure recovery and mass flow are presented for five diffusers having different initial rates of subsonic diffusion. Drag coefficient and diffuser-discharge Mach number are included in order to increase the utility of the data. The configurations have the same over-all length, combustion-chamber size, and supersonic compression.

The investigation was conducted at the NACA Lewis laboratory.

SYMBOLS

The following symbols are used in this report:

A area

A_m external maximum cross-sectional area (0.360 sq ft)

C_D external drag coefficient

$$C_D = \frac{D}{q_0 A_m}$$

$$= \frac{\left[\gamma p_4 M_4^{\,2} + (p_4 - p_0)\right] A_4 \cos\alpha + (p_b - p_0) A_b \cos\alpha - \gamma p_0 M_0^{\,2} A_0 - C_{T-D}}{q_0 A_m}$$

C_{T-D} thrust-minus-drag coefficient, $\frac{T - D}{q_0 A_m}$

D drag force

D_e equivalent diameter of inlet annulus, $4A/s$ (hydraulic diam., 2.73 in.)

L length of model from cowl lip to base, 55.86 in.

M Mach number

m mass flow

$\frac{m_4}{m_0}$ mass-flow ratio, $\frac{\text{mass flow at diffuser discharge}}{\rho_0 V_0 A_1}$

P total pressure

p static pressure

q dynamic pressure, $\gamma p M^2/2$

s wetted perimeter of inlet annulus

T thrust, net force in flight direction determined by application of momentum theorem to air passing through model

V velocity

x longitudinal station

α angle of attack, deg

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γ ratio of specific heats for air

θ geometric angle

ρ mass density of air

φ angle between oblique shock and model axis

Subscripts:

b base of strain-gage balance

c angle between cone surface and model axis

l angle of line joining cone tip and cowl lip with axis of model

x longitudinal station

0 free stream

1 leading edge of cowl lip

4 diffuser discharge at constant-diameter section (with sting), station 46.875

4,1 diffuser discharge at constant-diameter section (without sting), station 46.875

APPARATUS AND PROCEDURE

The general arrangement of the models used in this investigation is the same as that used for a number of investigations in the Lewis 8- by 6-foot supersonic wind tunnel first reported in reference 6. A schematic diagram of the model is shown in figure 1. Five configurations of subsonic-diffuser area variation shown in figure 2 were achieved by two cowls combined with various fairings of the centerbody. Half-angle cones of 25° were used for all configurations except one in which the half-angle was increased to 30°. Variations in the cone tip projection relative to the cowl lip were made by means of spacers in the centerbody at a station well inside the subsonic diffuser. The two cowls had the same nominal lip diameter, but one was contoured for a more rapid increase in internal area than the other. The initial internal divergence angle of the two cowls was 8° and 11°, respectively. Both cowls would be classified as having sharp lips. The length from the cowl lip to the base was 55.86 inches and the maximum diameter was 8.125 inches for all models.

For convenience in identification of the various combinations, a code number has been assigned in the following manner: 25-43-12 indicates, for example, a 25° cone half-angle, a 43° spike-tip-to-cowl-lip angle, and a 12-percent area change per initial hydraulic diameter; 25-43-0(3.5) indicates the same supersonic configuration as before with zero diffusion for 3.5 lengths of hydraulic diameter.

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Air flow through the model was controlled by means of a movable plug at the base. The ratio of the mass of air flowing through the model to the maximum that could flow based on cowl entrance area was computed by means of the average of eight static pressures measured at station 36.7, the flow area at the plug, and isentropic relationships. Total-pressure recovery was computed by the same means. All pressures were measured by means of the NACA Digital Automatic Multiple Pressure Recorder.

Axial force, normal force, and pitching moment were measured by means of an internally mounted self-resolving deflection balance. Remote indication of the forces was achieved by means of electric strain gages and servo-amplifier-driven self-balancing slide wires.

The occurrence of pulsating flow was determined by three simultaneous methods. A miniature variable-reluctance pressure transducer was located at station 41 in the model and connected to one channel of a recording oscillograph. The axial-force measuring circuit of the balance was connected to a second channel of the recording oscillograph. An observer was stationed at the viewing screen of the schlieren apparatus. It is believed that the onset of pulsing was determined consistently within the order of 1 percent of maximum mass-flow ratio.

RESULTS AND DISCUSSION

In order to establish a reference for determining the effect of the various alterations to the subsonic diffuser, a basic inlet designated 25-43-12 was included in the series investigated. The 12-percent area variation per hydraulic diameter gives the same order of subsonic-diffuser area variation as the familiar 6° equivalent conical diffuser. The performance of the basic inlet, 25-43-12, is presented in figure 3(a).

Because of the uncertainty of estimating the growth of boundary layer which might induce choking in a constant-area section at the entrance to the subsonic diffuser, an intermediate area variation of 3.85 percent per hydraulic diameter was investigated in the 25-43-3.85 model. The performance of this model was taken from reference 7 and is presented in figure 3(b). Reducing the initial average rate of

subsonic area variation from 12 to 3.85 percent improved the stable range from about 8 to 17 percent at a Mach number of 2.0 with little if any change in critical pressure recovery. The change to the 25-43-3.85 model also involved changing from the 11° to the 8° cowl.

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The diffusion rate was reduced to essentially zero for 3.5 hydraulic diameters in the 25-43-0(3.5) inlet. The physical area of this section, designated the stabilizing length, was allowed to diverge at the rate of about 1.0 percent per hydraulic diameter in order to compensate somewhat for the growth of boundary layer. The performance of the 25-43-0(3.5) diffuser is presented in figure 3(c). The stable mass-flow range was 46 percent for this diffuser at a Mach number of 2.0. The peak pressure recovery for a Mach number of 2 occurred at critical mass-flow ratio and was 0.845.

Two configurations having 1 and 2 hydraulic diameters of stabilizing length, respectively, were investigated in order to establish the minimum requirements of this method of stabilizing the inlet. The performance of the 25-43-0(1) and the 25-43-0(2) inlets is presented in figure 4.

The effect of the stabilizing length on the minimum stable mass-flow ratio is summarized in figure 5(a). The basic diffuser achieved an 8-percent stable mass-flow range at a Mach number of 2.0. The alteration to the centerbody to provide 1 hydraulic diameter of stabilizing length resulted in a reduction of the minimum stable mass-flow ratio possible. In fact, the 25-43-0(1) diffuser had essentially no subcritical mass-flow range at a Mach number of 2. A further alteration of the centerbody to provide 2 hydraulic diameters of stabilizing length had a favorable influence on the flow and permitted a mass-flow-ratio range of 11 percent without pulsation at a Mach number of 2.0. The results of this study indicate that a minimum of 2.25 hydraulic diameters of stabilizing length is required to achieve the same stable mass-flow range as the diffuser with the 3.85 area variation rate.

The effect of increasing the stabilizing length indicated the same trend at a Mach number of 1.8 as at 2.0 with the one exception that the alteration for the 25-43-0(1) diffuser increased the mass-flow regulation range slightly at a Mach number of 1.8 rather than decreasing the regulation range as was observed for a Mach number of 2.0. The maximum mass-flow ratio for all the diffusers dropped to 0.93 at a Mach number of 1.8 because the cone was positioned for the oblique shock to intersect the cowl lip at a Mach number of 2.0. All the inlets were stable throughout the mass-flow range at a Mach number of 1.5, and therefore the minimum mass-flow ratio indicated on the curves is arbitrary.

The addition of the stabilizing length at the entrance to the subsonic diffuser might be expected to influence the subcritical total-pressure recovery in two ways. The pressure recovery could be reduced because of the additional friction losses incurred at a section in the diffuser where the flow Mach numbers are relatively high. The pressure recovery might be increased because of the favorable effect on diffuser efficiency that the stabilizing length might achieve by reducing velocity differences which exist in the entering flow. Figure 5(b) indi-
2894 cates the effect of stabilizing length on critical pressure recovery. At a Mach number of 1.5 the Mach number entering the subsonic diffuser is relatively high, and the addition of stabilizing length causes a gradual deterioration of pressure recovery from 0.95 for the 25-43-12 diffuser to 0.90 for the 25-43-0(3.5) diffuser. At a Mach number of 1.8 the entering Mach number is decreased, and the effect is less pronounced. At a Mach number of 2.0 the friction and mixing effects are apparently counterbalancing and the pressure recovery is essentially unaffected by changes in stabilizing length.

In order to investigate the effect that the presence of the vortex sheet near the inner surface of the cowl might have on the stable mass-flow range, the cone was moved by small increments to place the oblique shock slightly upstream, intersecting, and slightly inside of the cowl lip. This technique gives significant differences in the position of the vortex sheet relative to the cowl lip for mass-flow ratios near unity. The performances at a Mach number of 2.0 for the 25-42-12, 25-43-12, and the 25-44-12 diffusers are presented in figures 6(a), (b), and (c), respectively. Figures 7(a), (b), and (c) present the performance data at a Mach number of 2.0 for small movements of the oblique shock for the 25-42-0(3.5), 25-43-0(3.5), and the 25-44-0(3.5) diffusers, respectively. Figure 8 summarizes the effect of oblique-shock position on the minimum stable mass-flow ratio at a Mach number of 2.0. Values of cowl-position ratio less than 1 indicate that the inlet is spilling mass flow for critical conditions and that the vortex sheet from the shock intersection is external to the cowl at supercritical conditions. Values of cowl-position ratio greater than 1 indicate that the oblique shock is entering the cowl for critical conditions and therefore for steady flow the vortex sheet is always inside the cowl. The diffusers with 12-percent area variation were relatively insensitive to small changes in spike position. The diffusers with 3.5 hydraulic diameters of stabilizing length were markedly affected by the small movement of the oblique shock. Moving the oblique shock from inside the cowl to a cowl-position ratio of 0.978 resulted in a change in minimum stable mass flow from 0.45 to 0.79. The full significance of the sensitivity of the 0(3.5) diffusers to oblique-shock position cannot be readily evaluated in view of the fact that the inlet with the 12-percent diffuser did not provide any correlation between the position of the vortex sheet relative to the cowl lip and the stable mass-flow range. The

total linear travel of the spike indicated by the change in the cowl-position ratio of figure 8 is ±3.5 percent from the design position. Therefore it is apparent that a diffuser control system which acts to position the cone must have a precise action if pulsation is to be avoided.

Observations of the schlieren patterns during the testing of the 12-percent diffusers indicated that the limit of stable mass flow of these diffusers was, at least in part, due to separation of the flow on the cone surface. In order to investigate this phenomenon further, the cone angle of the 12-percent diffuser was altered to the configuration designated 30-48-12. The performance of the diffuser with the altered cone angle is presented in figure 9. The 30-48-12 configuration had a 15-percent stable mass-flow ratio range at a Mach number of 2.0, which compares with 5 percent for the 25-42-12 configuration. The reduction in cone surface Mach number achieved by changing the cone half-angle was not sufficient to eliminate separation. The change in cone angle resulted in a reduction of critical pressure recovery from 0.86 to 0.84. 2894

The performance of all the inlet configurations was investigated up to a 9° angle of attack. Figure 10 is a summary plot of the minimum stable mass flow for various angles of attack. The 25-43-0(1) diffuser had essentially no subcritical mass-flow range at any angle of attack. The curve for this diffuser represents the trend of the variation of maximum mass flow with angle of attack for all the diffusers. The variation of the minimum stable mass-flow ratio of the 25-43-12 diffuser was somewhat erratic with changing angle of attack. In general, this diffuser tended to oscillate at about the same value of absolute mass flow at all angles of attack. The 25-43-0(2) inlet also consistently began oscillating at a particular mass-flow value for all angles of attack. In contrast the 30-48-12 diffuser had essentially constant stable mass-flow range throughout the angle of attack investigated. The 25-43-0(3.5) diffuser displayed a radically different trend from the other diffusers investigated. The mass-flow regulation range of this diffuser is about constant up to 3.5°, at which angle the regulation range suddenly decreased to a value just slightly better than the other 25° diffusers. The effect of small movement of the cone tip position persisted throughout the angle-of-attack range. For the 25-44-0(3.5) diffuser the stabilized performance was maintained to about a 5° angle of attack. In the angle-of-attack range from 5° to 6°, the minimum stable mass flow achieved depended on which direction the test points were approached, as is indicated by the discontinuous form of the curve.

In general, the experimental data indicates that reducing the rate of diffusion at the entrance to the subsonic portion of an external compression supersonic inlet did permit various degrees of stable subcritical operation. None of the various theoretical concepts is

sufficiently precise to permit a rational treatment of the effect of stabilizing length on the inlet flow without experimental data. The presence of separation from the cone surface in various amounts was observed to have an important bearing on the range of stable mass flow that could be achieved. The relation between the mechanism of separation and the function of the stabilizing length is not as yet fully understood.

SUMMARY OF RESULTS

The effect of various rates of subsonic-diffuser area variation on the stable subcritical mass-flow range of 25° half-angle conical supersonic diffusers designed for operation at a Mach number of 2.0 can be summarized as follows:

1. Reducing the initial rate of subsonic diffusion per hydraulic diameter progressively from 12 to 3.85 to 0 percent was effective in improving the variation of mass flow that could be achieved without pulsation. Variation in length of the zero diffusion section indicated that at a Mach number of 2.0 and zero angle of attack 1 hydraulic diameter of stabilizing length actually reduced the stable mass-flow range. The addition of stabilizing length greater than 1 hydraulic diameter progressively improved the stable mass-flow regulation range. The diffuser with 3.5 hydraulic diameters of stabilizing length had a pulsation-free range of 46 percent.

2. The incorporation of stabilizing length in the subsonic diffuser had little if any effect on the critical pressure recovery at a Mach number of 2.0 and zero angle of attack. The effect of the stabilizing length on the pressure recovery of the Mach number 2.0 design was pronounced at a Mach number of 1.5. The critical pressure recovery of the inlet with 3.5 hydraulic diameters of stabilizing length was 0.90 at a Mach number of 1.5, which compares with 0.95 for the diffuser without stabilizing length.

3. The stable mass-flow range of the diffuser with 3.5 hydraulic diameters of stabilizing length was very sensitive to small changes in cone position. At a Mach number of 2.0 and zero angle of attack, moving the oblique shock from slightly inside the cowl lip to slightly outside changed the minimum stable mass-flow ratio from 0.49 to 0.79.

4. The stable mass-flow range for the diffuser with no stabilizing length was 8 percent at a Mach number of 2.0 and zero angle of attack. Increasing the cone half-angle from 25° to 30° increased the stable mass-flow range to 15 percent. The change in cone angle resulted in a reduction of critical pressure recovery from 0.86 to 0.84.

5. The stable range of the diffuser with 3.5 hydraulic diameters of stabilizing length had a tendency to improve with increasing angle of attack until a critical angle was reached, at which point the stable range suddenly decreased to a value just slightly better than the comparable diffuser without stabilizing length. The critical angle of attack was 3.5° at a Mach number of 2.0 for the cone position which placed the oblique on the cowl lip.

Lewis Flight Propulsion Laboratory 2894
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 3, 1953

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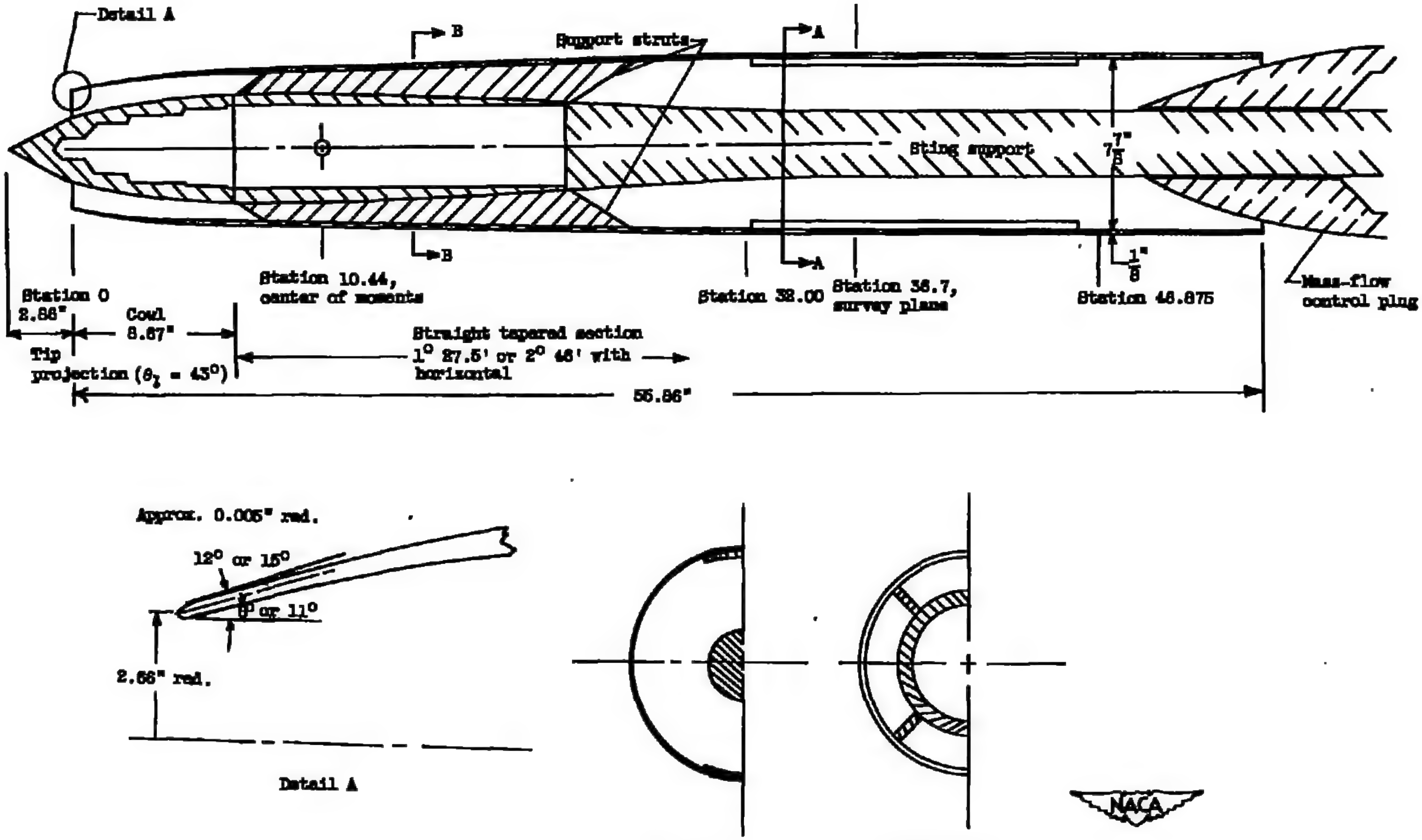

Figure 1. - Schematic diagram showing principal dimensions of model.

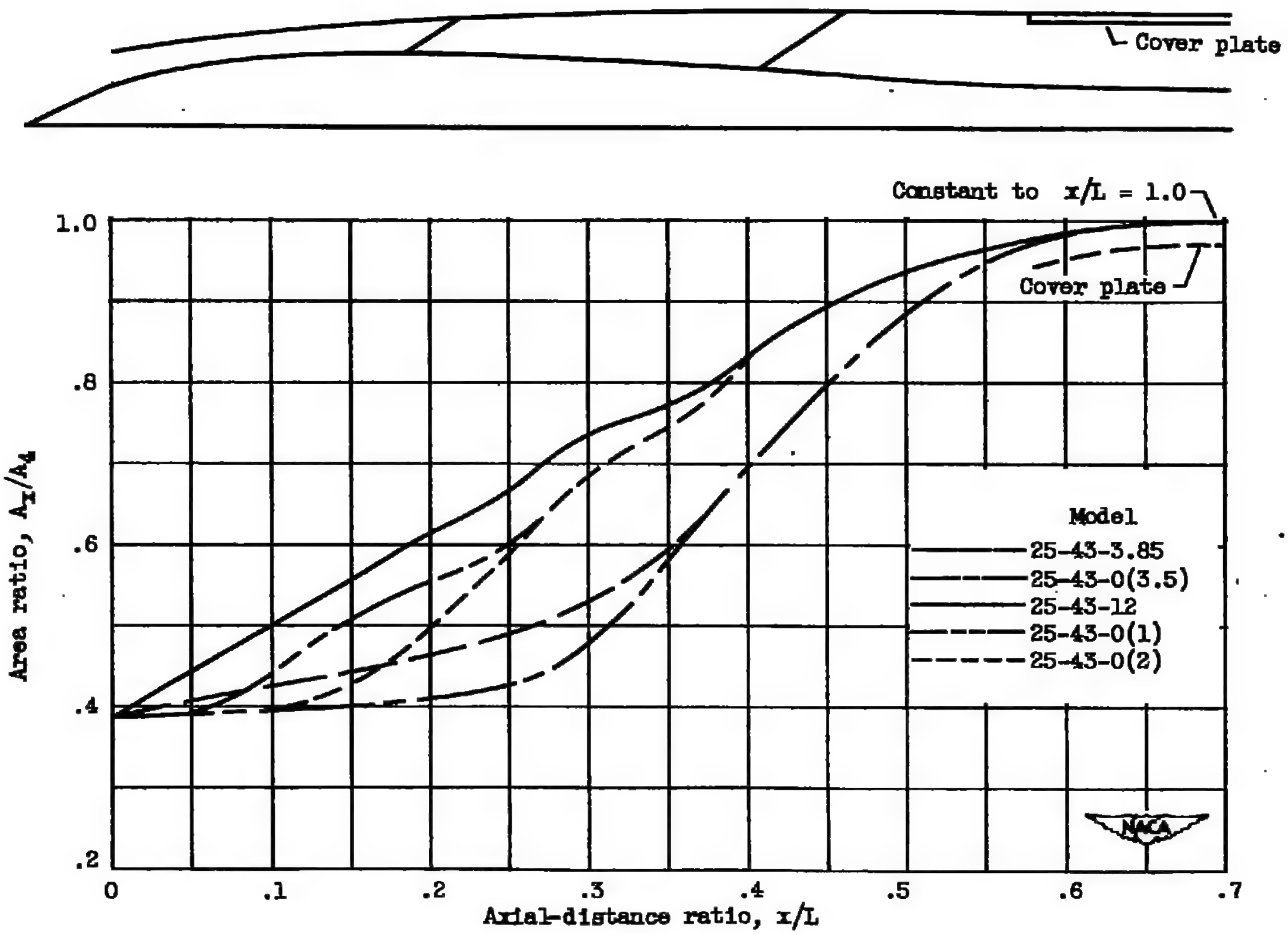

Figure 2. - Subsonic-diffuser area variation.

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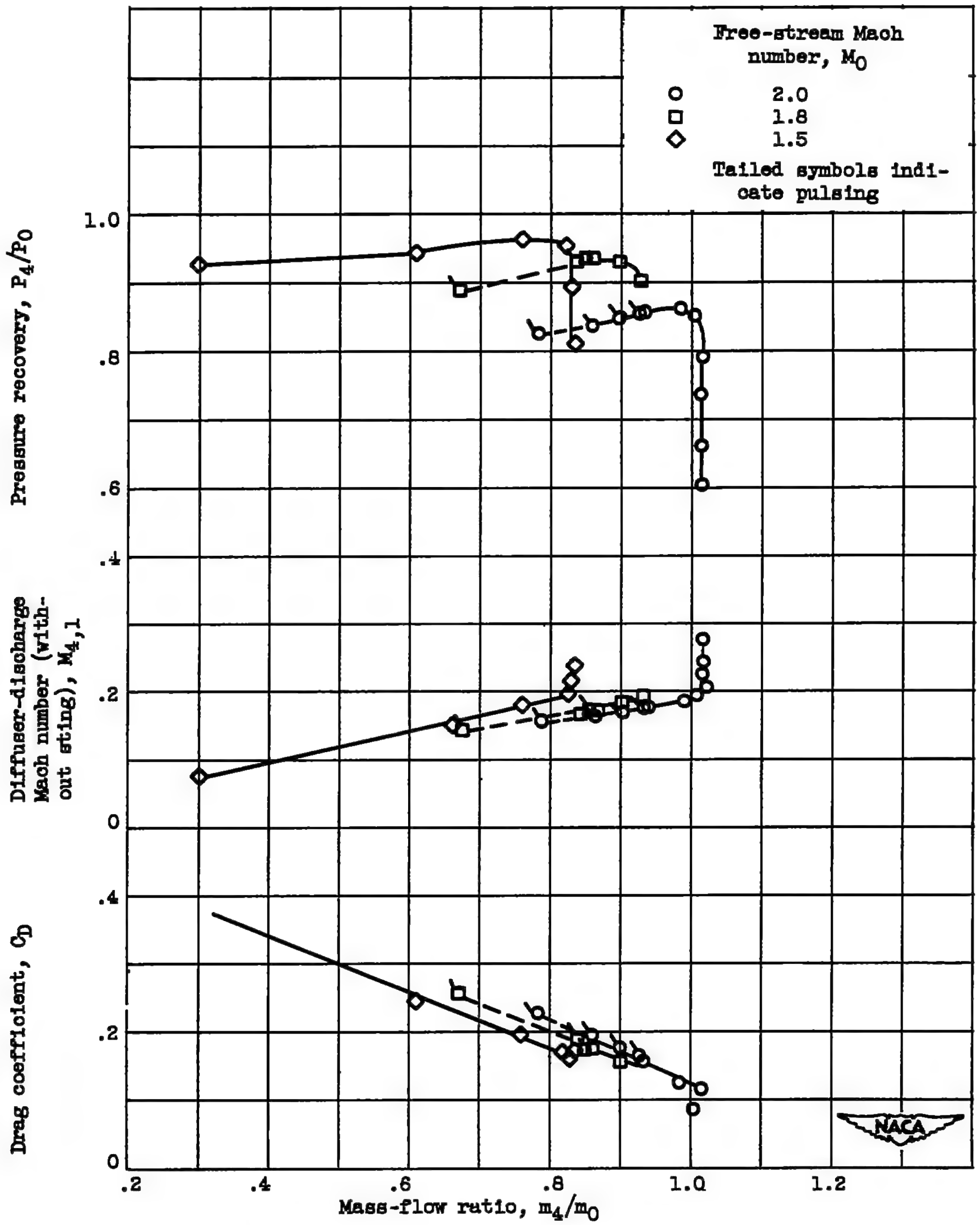

(a) Twelve-percent diffuser, model 25-43-12.

Figure 3. - Variation of characteristics of diffuser for range of Mach numbers. Zero angle of attack.

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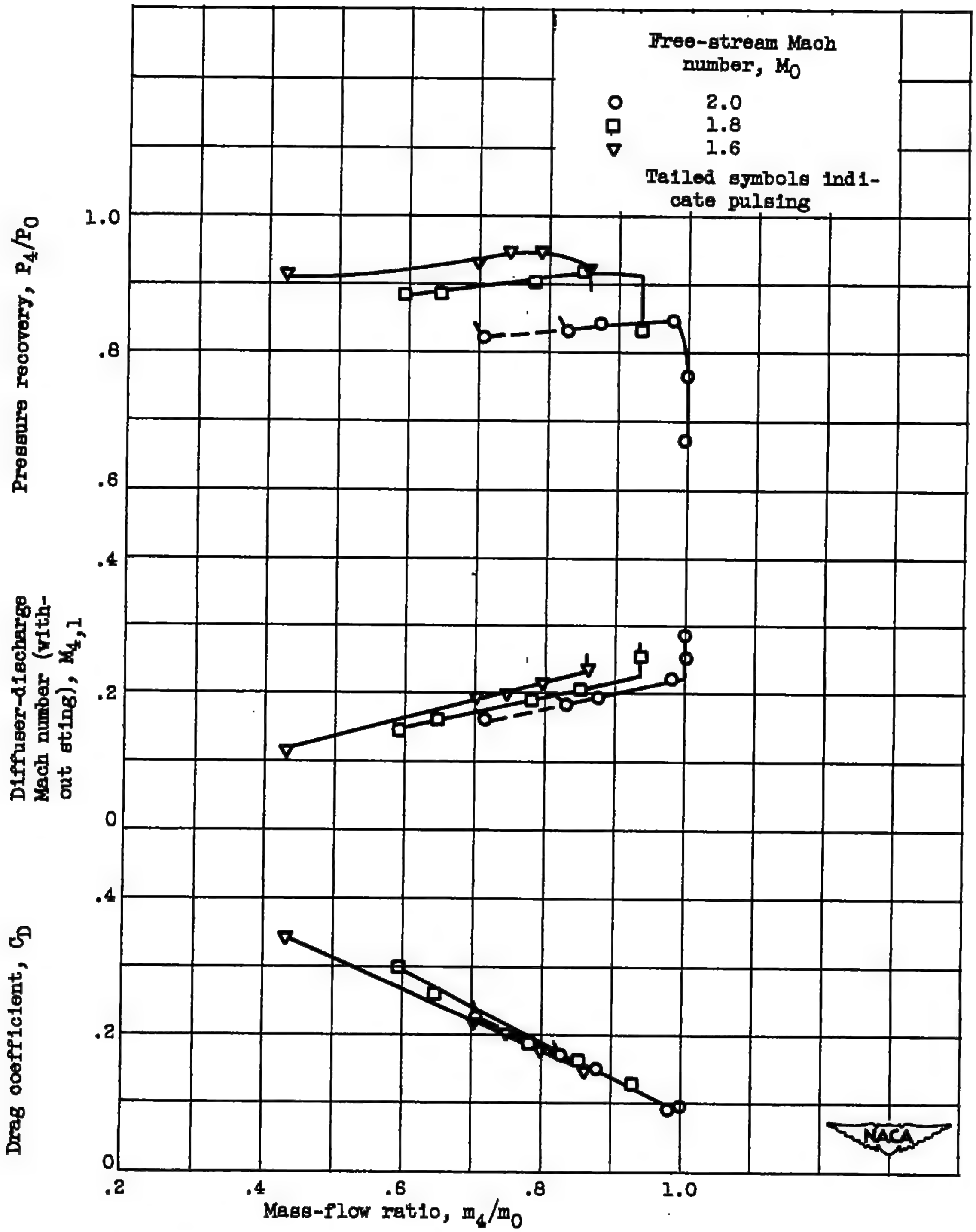

(b) 3.85-Percent diffuser; model 25-43-3.85.

Figure 3. - Continued. Variation of characteristics of diffuser for range of Mach numbers. Zero angle of attack.

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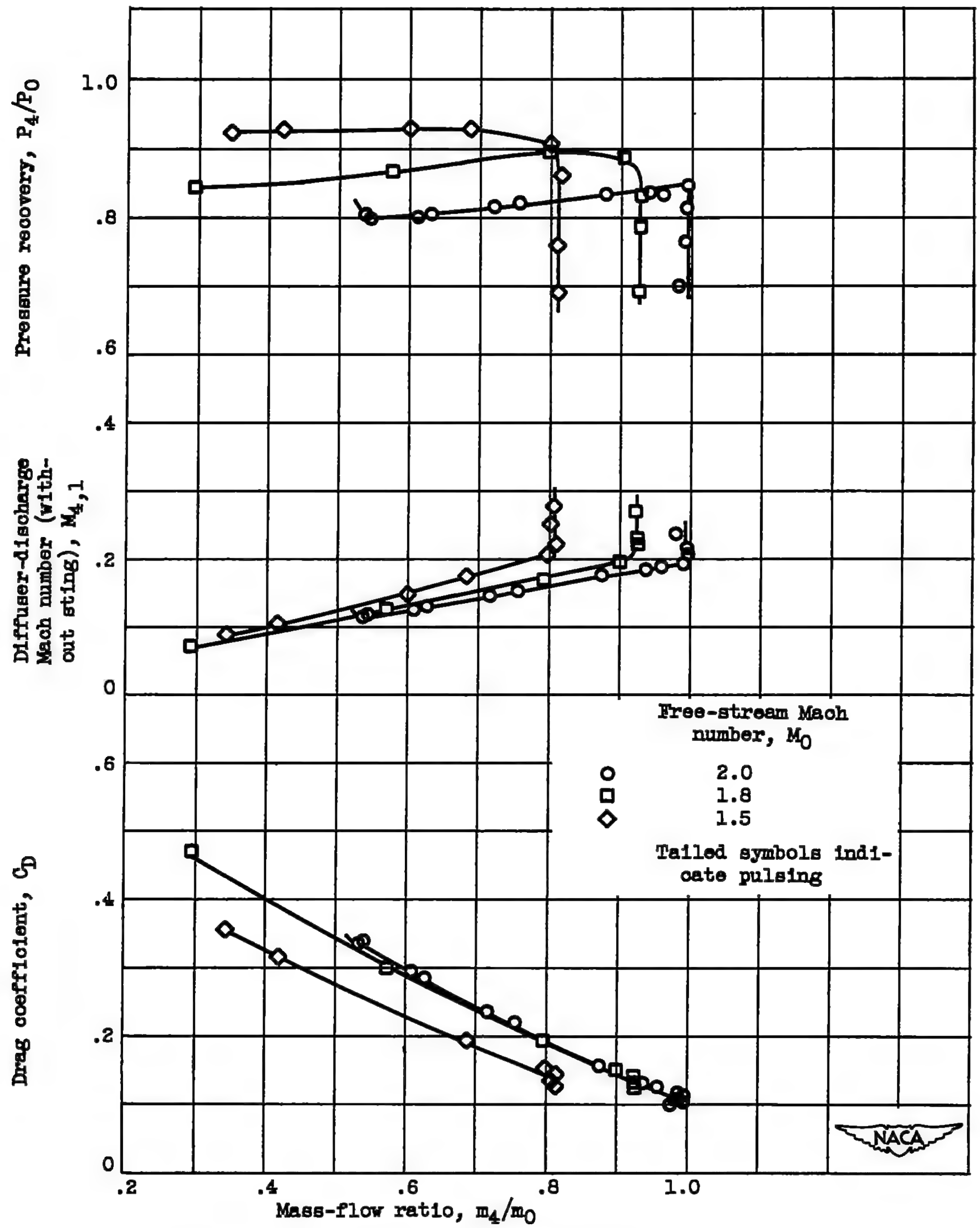
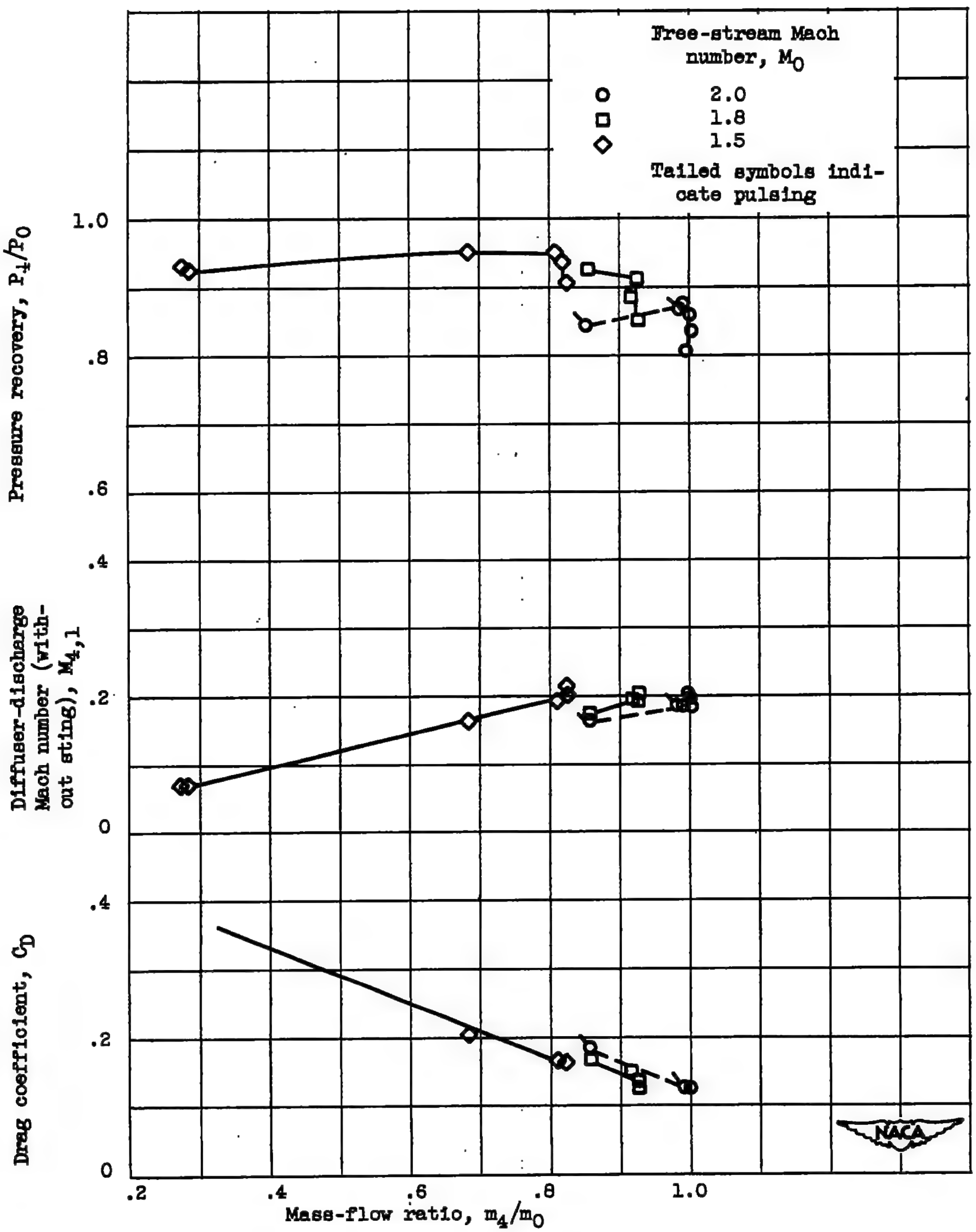


(c) Zero-percent diffuser; model 25-43-0(3.5).

Figure 3. - Concluded. Variation of characteristics of diffuser for range of Mach numbers. Zero angle of attack.



(a) One hydraulic diameter; model 25-43-0(1).

Figure 4. - Characteristics of diffuser with zero diffusion. Zero angle of attack.

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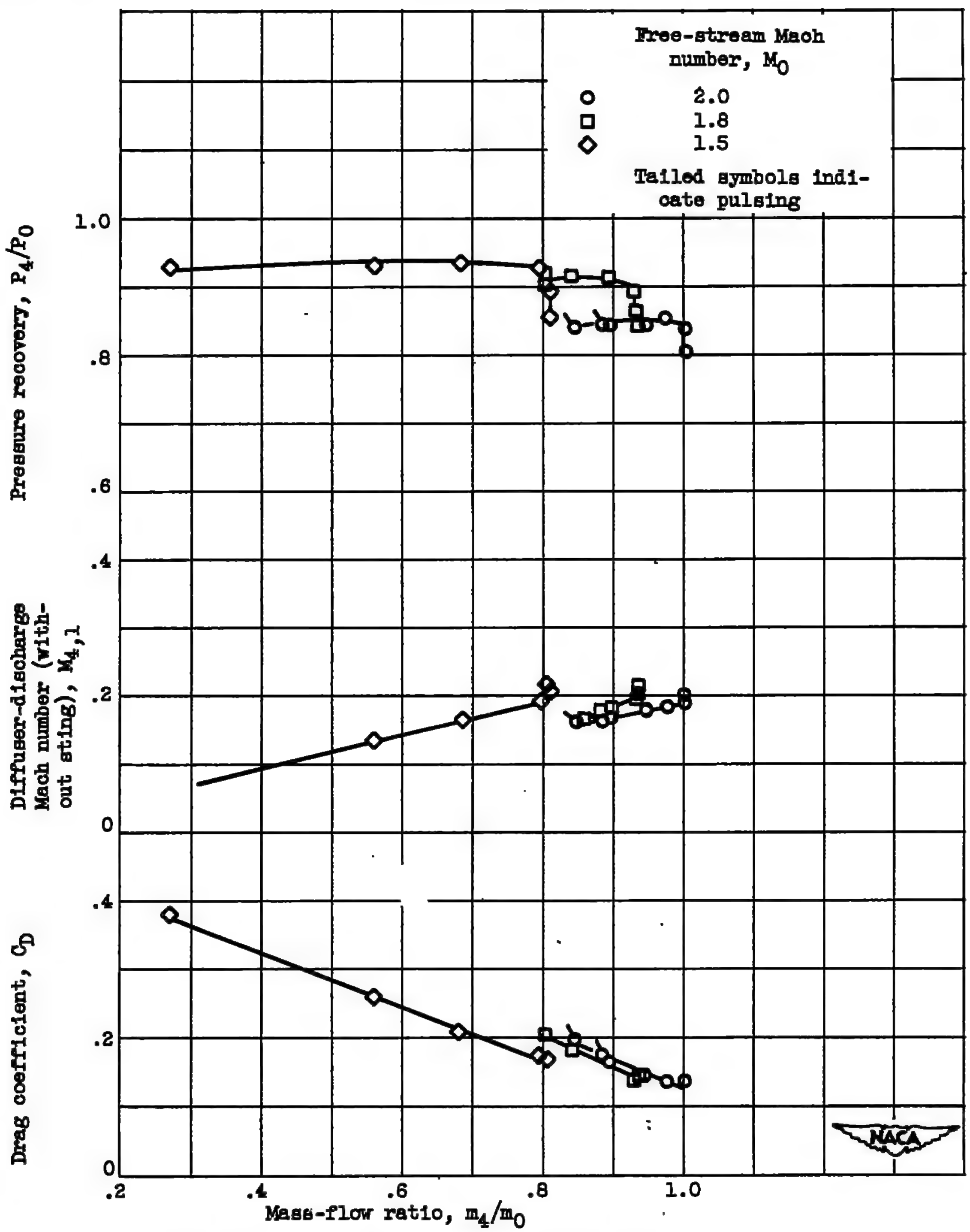

(b) Two hydraulic diameters; model 25-43-0(2).

Figure 4. - Concluded. Characteristics of diffuser with zero diffusion Zero angle of attack.

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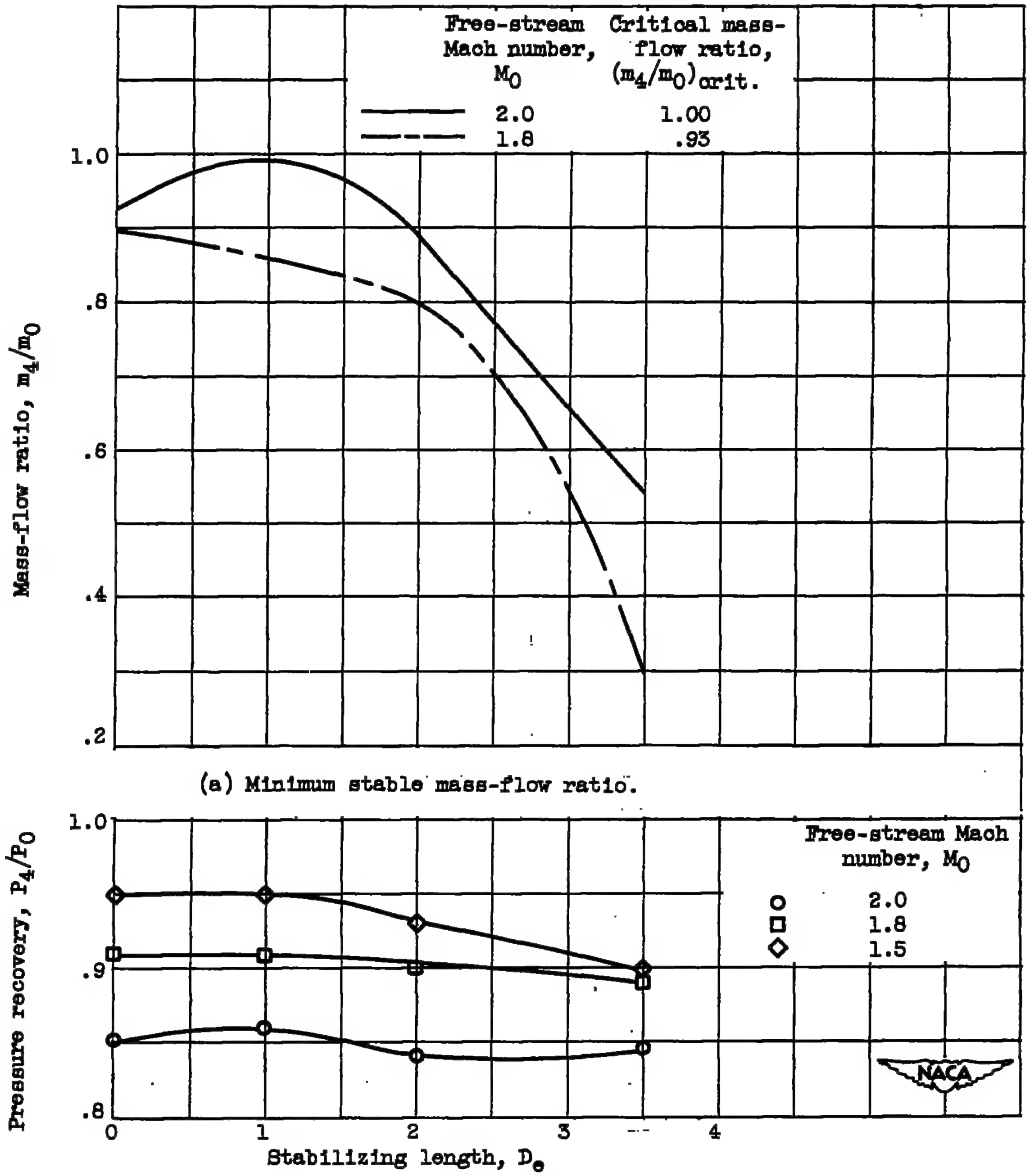

(b) Critical pressure recovery.

Figure 5. - Effect of stabilizing length. Zero angle of attack.

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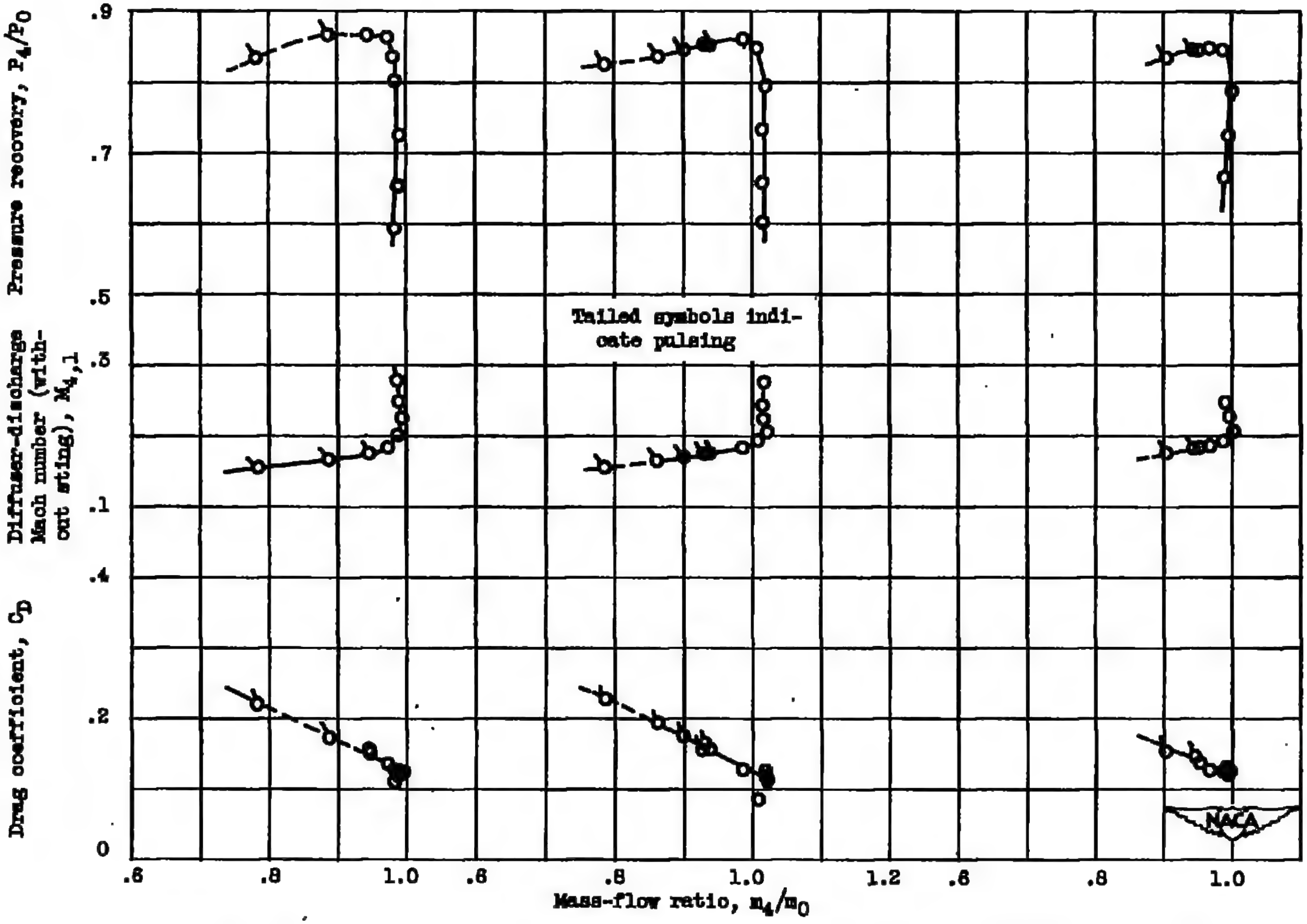
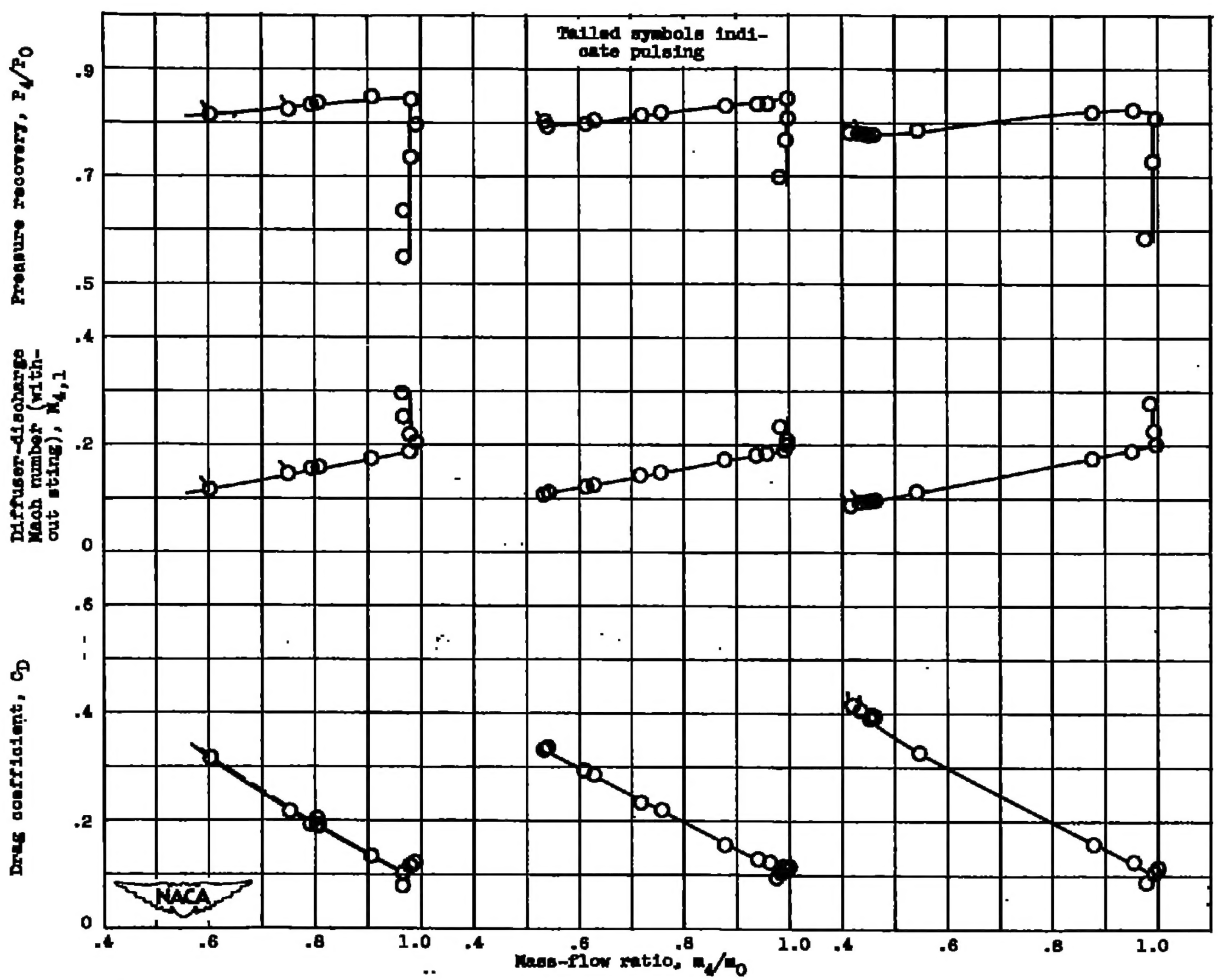


(a) Upstream spike position; model 25-42-12.

(b) Design spike position; model 25-43-12.

(c) Downstream spike position; model 25-44-12.

Figure 6. - Characteristics of 12-percent diffuser. Free-stream Mach number, 2.0; zero angle of attack.



(a) Upstream spike position; model 25-42-0(3.5)

(b) Design spike position; model 25-43-0(3.5).

(c) Downstream spike position; model 25-44-0(3.5).

Figure 7. - Characteristics of zero-percent diffuser. Free-stream Mach number, 2.0; zero angle of attack.

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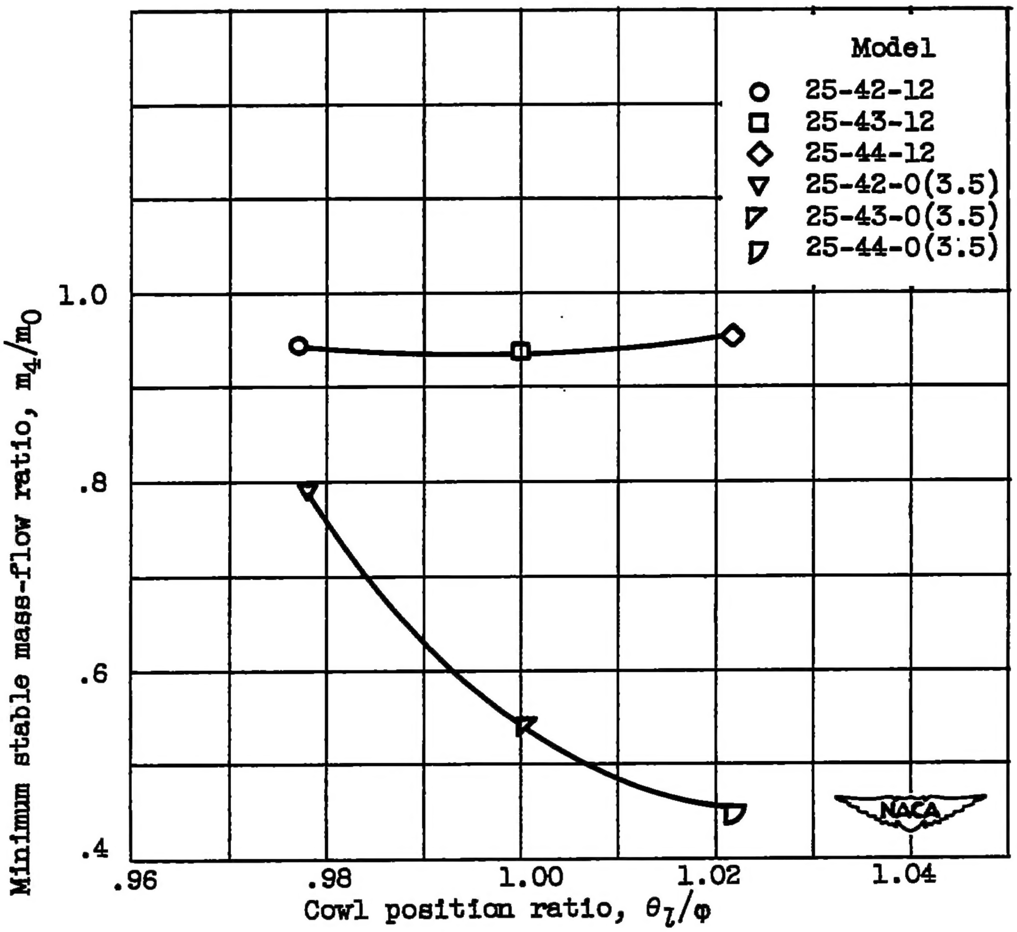

Figure 8. - Effect of spike position on stable mass-flow range. Free-stream Mach number, 2.0; zero angle of attack.

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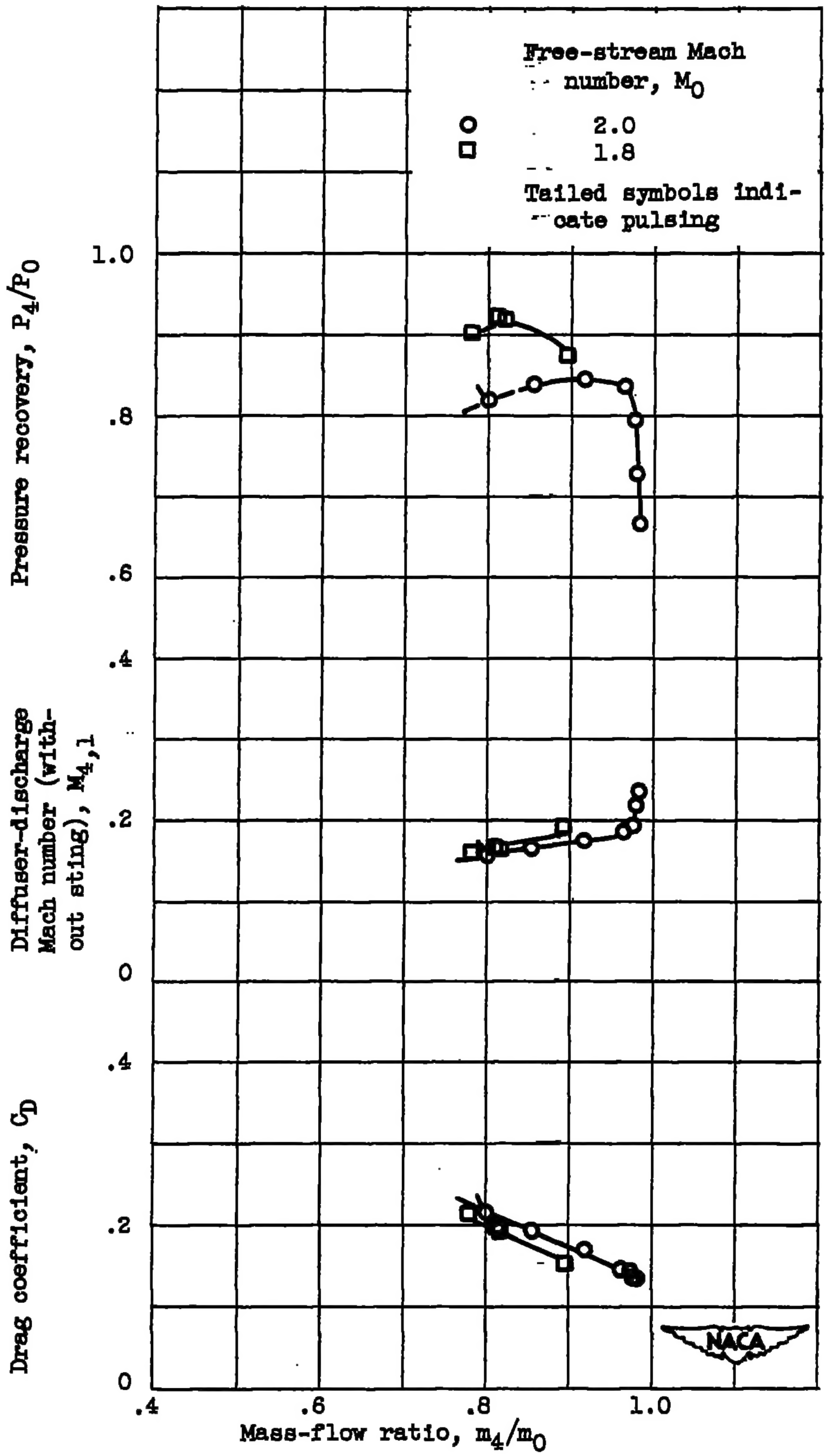

Figure 9. - Characteristics of 12-percent diffuser with 30° cone. Model 30-48-12; zero angle of attack.

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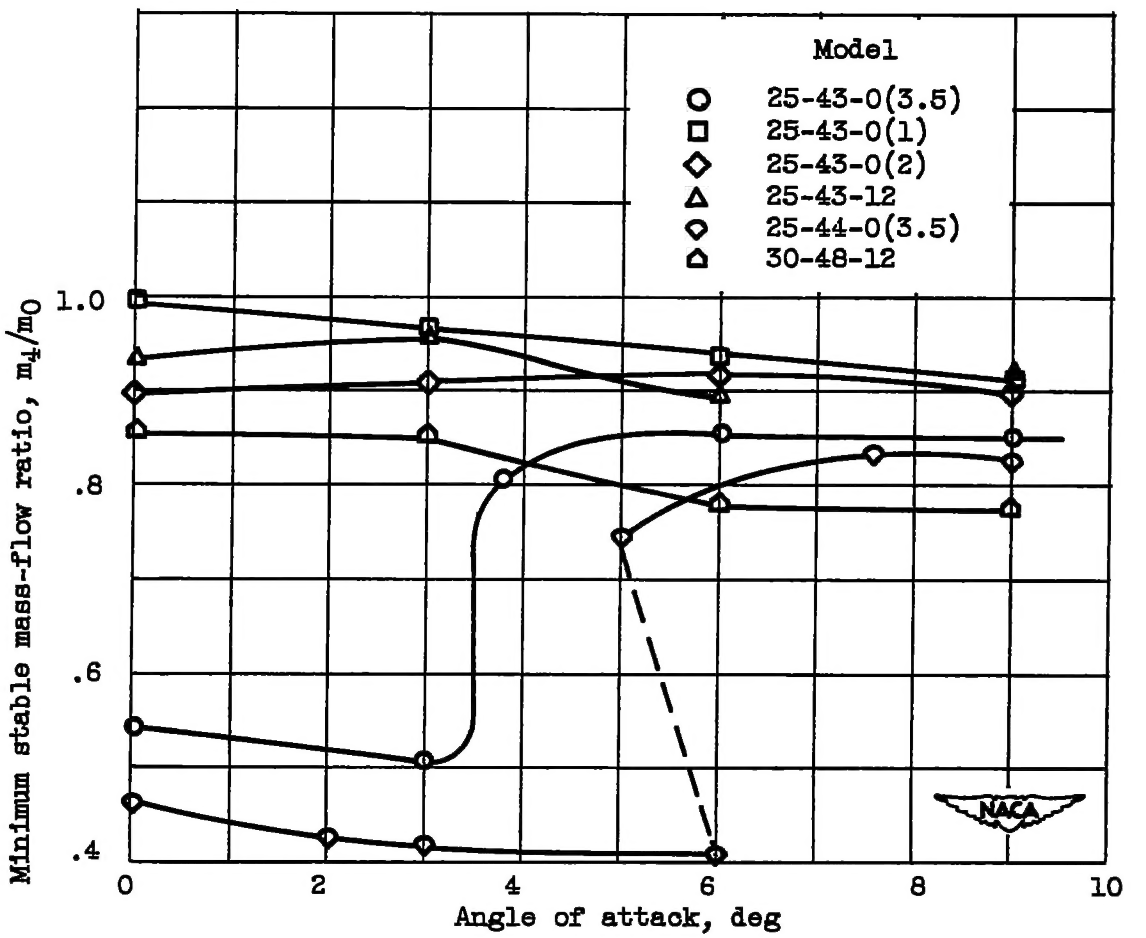

Figure 10. - Variation of minimum stable mass-flow ratio with angle of attack. Free-stream Mach number, 2.0.